Introduction:

The prototype MICE RF module under test in the MTA Hall was assembled in Lab-6 at Fermilab and includes a 4 foot diameter 16.5 inch long copper RF cavity inside a 5 foot diameter 3 foot long stainless steel vacuum vessel [1]. It is also referred to as the MICE Single Cavity Module or Single Cavity Test System. Figure 1a shows the system installed in the MTA experimental hall. The vacuum system configuration is similar to other high-vacuum systems in operation around the lab. One notable exception is a pair of large (42 cm diameter), thin (0.38 mm thick) curved windows [2] made of beryllium mounted on the RF cavity [3], figure 1b, inside the vacuum vessel. The vacuum system schematic is shown in figure 2.

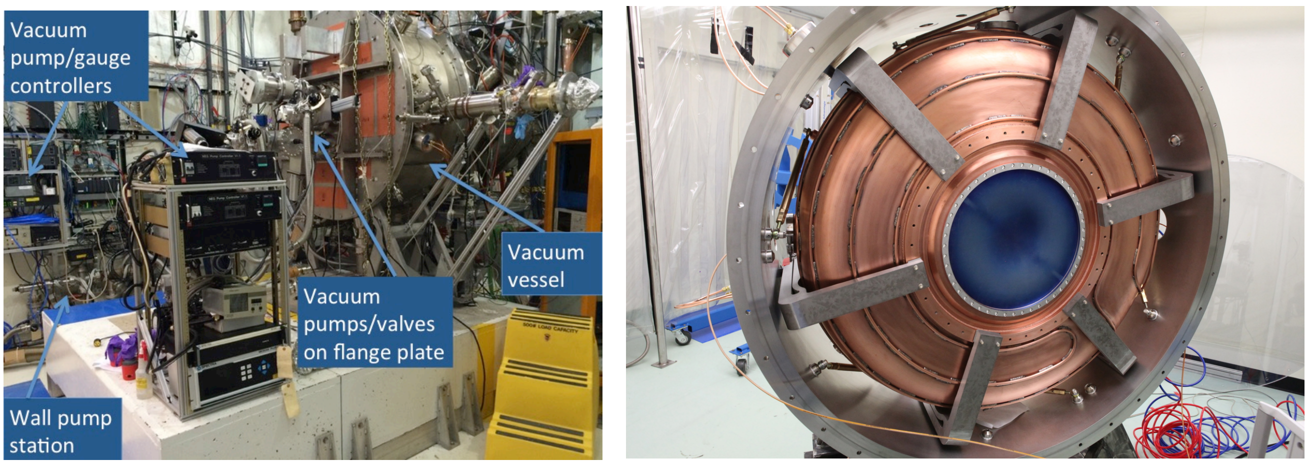


Figure 1. (a) The MICE vessel in the MTA hall. (b) Be window (blue).

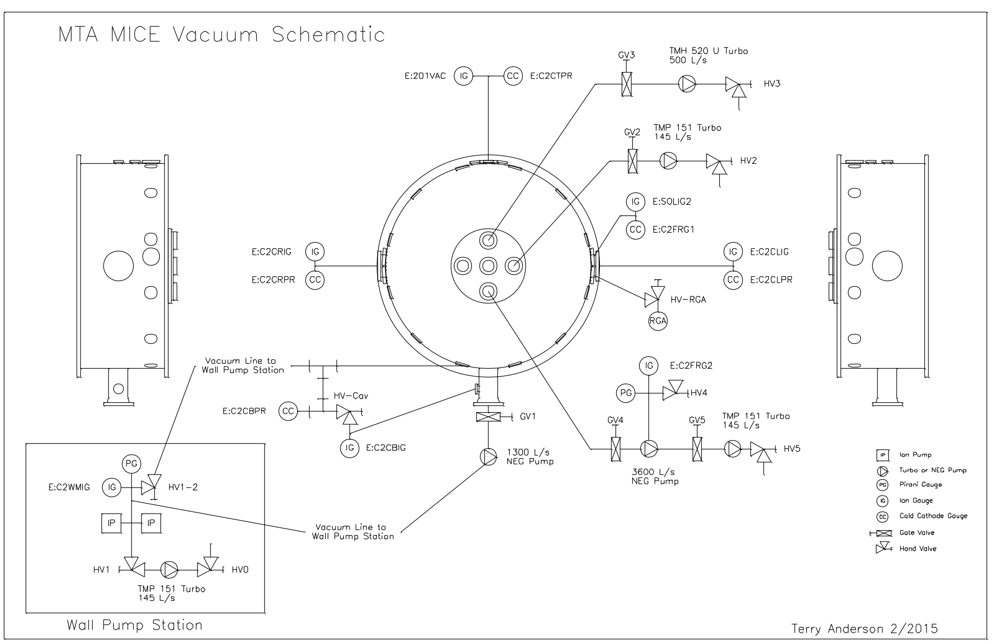


Figure 2. MTA MICE Vacuum Schematic

Vacuum Performance:

During a test pumpdown starting on 1/15/2015 measurements were made to characterize the vacuum system. Figure 4 shows the performance of the system during this pumpdown. The pressure was measured via an ion gauge on the top of the vessel. The gauge is connected to the top of the cavity by 33 centimeters of stainless steel tubing (Figure. 3) with a conductance of 1.6 L/s. The estimated pressure drop along this conductance is $2.0(10)^{-8}$ Torr.

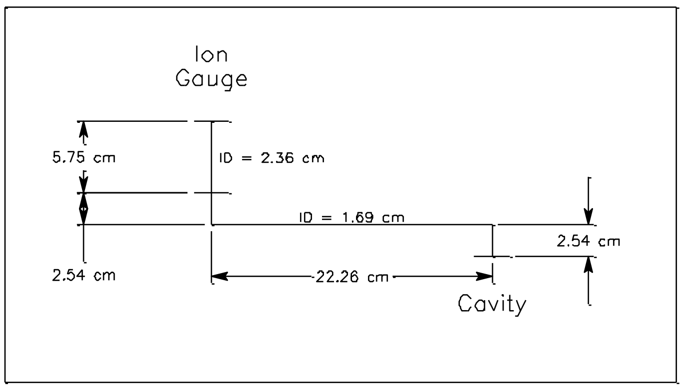


Figure 3. Ion gauge to cavity conductance geometry.

A nitrogen to vacuum leak was discovered in the number 1 actuator during the pumpdown and was mitigated by pulling a rough vacuum on the nitrogen side of the leak. The effect of this can be seen in figure 4 where the pressure changes from $9.0(10)^{-8}$ to $8.0(10)^{-8}$ Torr.

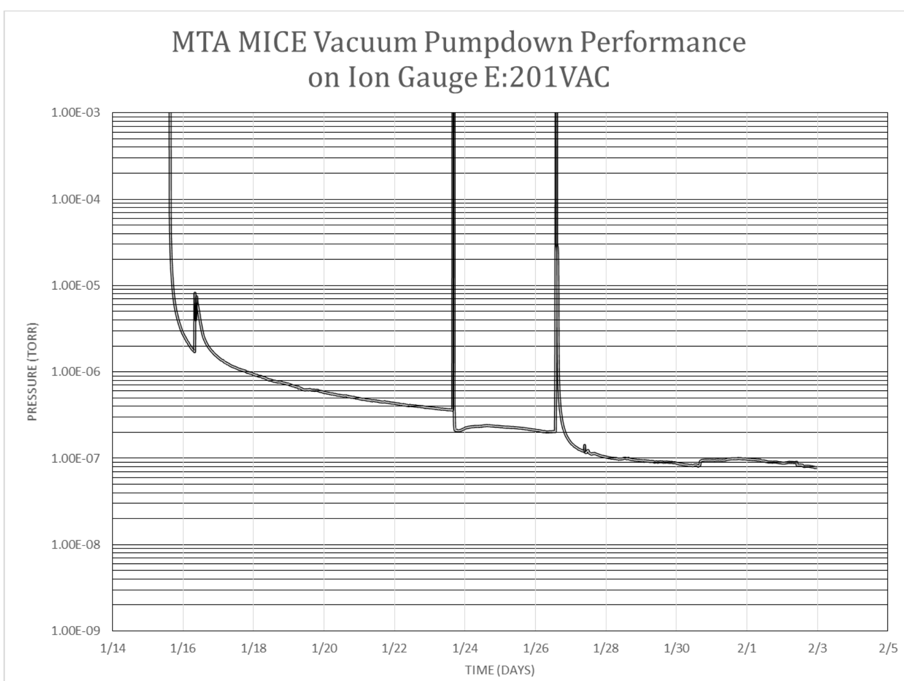


Figure 4. January 2015 pumpdown performance.

Table 1. Significant events during January 2015 pumpdown test.

Date	Event Description
1/15/15	Turbos started about 15:00.
1/16/15	RGA turned on.
1/23/15	Determined source of high 44 peak and found N2 leak in #1 (push) actuator. High 44 peak is due to hot filaments of IG's and RGA. Turned off RGA.
1/26/15	Activated 1300 NEG at bottom of Cavity.
1/27/15	Activated 3600 NEG.
1/28/15	Opened 3600 NEG to system.
1/30/15	System put in final configuration. Only pumping with IP, 1300 NEG, and 3600 NEG.
2/2/15	Pulled vacuum on leaking #1 actuator line.

The vessel is pumped on by three turbo molecular pumps (1 – 500 L/s Balzers TMH 520U and 2 – 145 L/s Leybold TMP 151's). They are connected to the vessel by a manifolding system with various conductances between the pumps and the vessel. All pumps are connected to the vessel by a 3" to 4" reducer and a 4" gate valve. The reducer has a conductance of 118 L/s and the valve has a conductance of 1700 L/s. The 500 L/s pump (attached at GV3) has an additional 4" to 6" reducer, with a conductance of 228 L/s, connecting it to the valve. One of the 145 L/s pumps (attached at GV4) has a getter pump assembly (3600 L/s) and another 4" gate valve in line with the other gate valve. When the conductances and entrance effects are accounted for the effective pump speeds are 63 L/s at GV2, 70 L/s at GV3, and 60 L/s at GV4.

The cavity is pumped at the bottom of the vessel through the wall pump station. The pump station has a 145 L/s turbo and a 30 L/s ion pump. They are connected to the 1300 L/s NEG (non-evaporative getter) pump at the bottom of the vessel. The connections are made through two long flexible stainless steel tubes with a total conductance on the order of 50 L/s. This would give an effective pumping speed on the order of 40 L/s at the NEG assembly (at GV1). The conductance from the NEG assembly to the cavity is 508 L/s, so the effective pumping speed on the cavity is about 35 L/s.

An effort was made to understand what the gas loads are from the vessel, the cavity, and miscellaneous components (cabling, instrumentation, supports, etc.). After eleven days of pumping the total gas load is approximately $4.3(10)^{-5}$ Torr-L/s. The contribution of the nitrogen leak is about $2(10)^{-6}$ Torr-L/s, so the real gas load is about $4.1(10)^{-5}$ Torr-L/s. The surfaces internal to the cavity and coupler arms account for about 24% of the total gas load ($9.84(10)^{-6}$ Torr-L/s) and the remainder ($3.12(10)^{-5}$ Torr-L/s) is accounted for by the components external to the cavity. Assuming a uniform specific outgassing rate these numbers would indicate a rate on the order of $2.2(10)^{-10}$ Torr-L/s-cm^2, this would be consistent with unbaked stainless steel and copper.

When the cavity is in actual operation all the turbos will be valved out and turned off. At that time the only pumping on the system will be from the two NEG pumps and the Wall Pump Station ion pump. The 1300 L/s NEG will pump on the internal cavity volume and the 3600 L/s NEG will pump on the vessel volume. The ion pump is used to pump those gasses not pumped by the NEG's. The 1300 L/s NEG has an effective pumping speed on the cavity of 281 L/s and the 3600 L/s NEG has an effective pumping speed on the vessel of 104 L/s. If the cavity volume was vacuum tight from the vessel volume the stated pumping would be sufficient to provide a pressure of $3.5(10)^{-8}$ Torr in the cavity and $3.0(10)^{-7}$ Torr in the vessel. In the current test configuration this is not the case though.

In the current configuration the cavity volume and vessel volume communicated with each other through an annulus in the bottom cavity pump port and slots in the coupler arms for the coupler cooling tubes. Figure 5 is a schematic of this configuration. The conductance between the vessel and cavity pump port is about 0.42 L/s and the conductance between the cavity and vessel at the couplers is on the order of 46 L/s (assumes a 1 cm^2 orifice area at 4 locations). The coupler conductance is not known specifically, so it can be used as a variable input for a mass balance model using figure 5. Figure 6 is the results of that model using a total gas load of 4E-5 Torr-L/s and the coupler conductance as a variable.

Figure 5.Vacuum Schematic of Operational Pumping

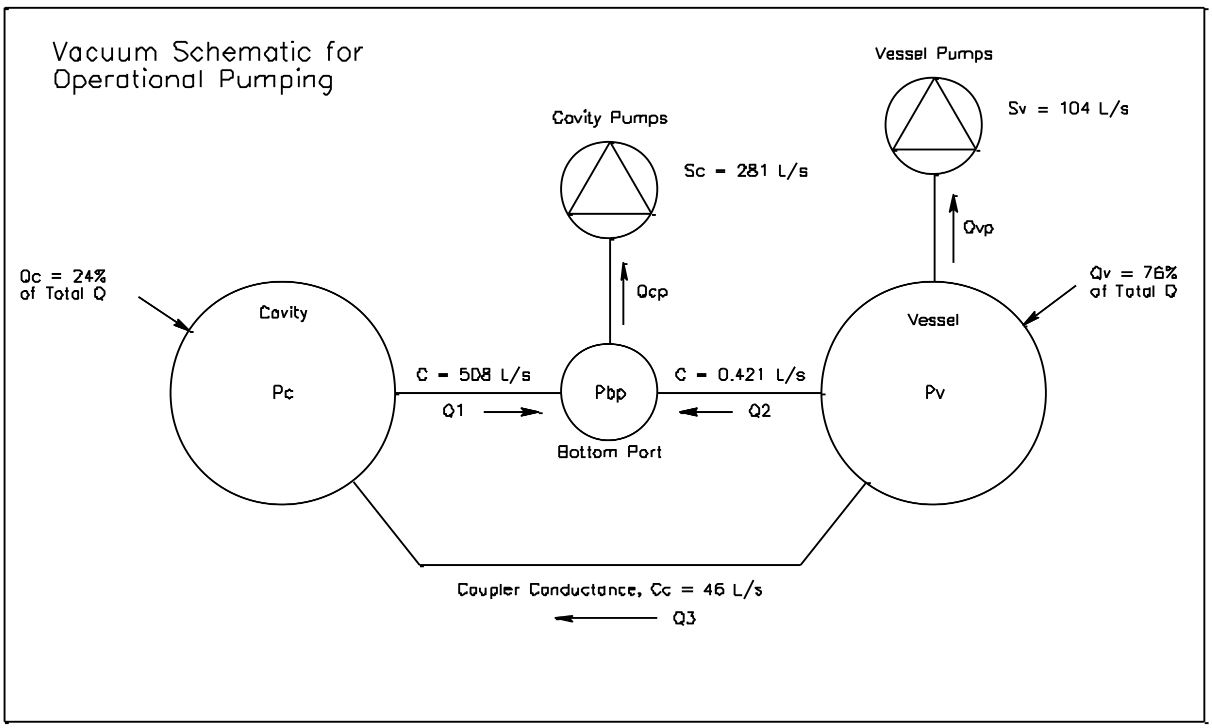
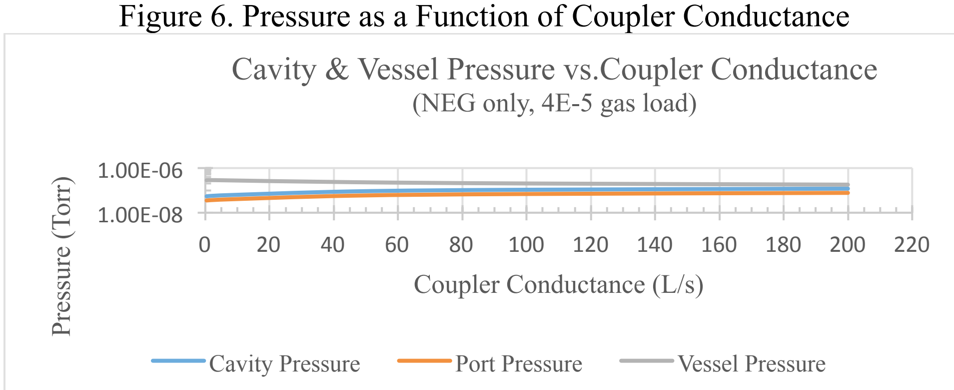
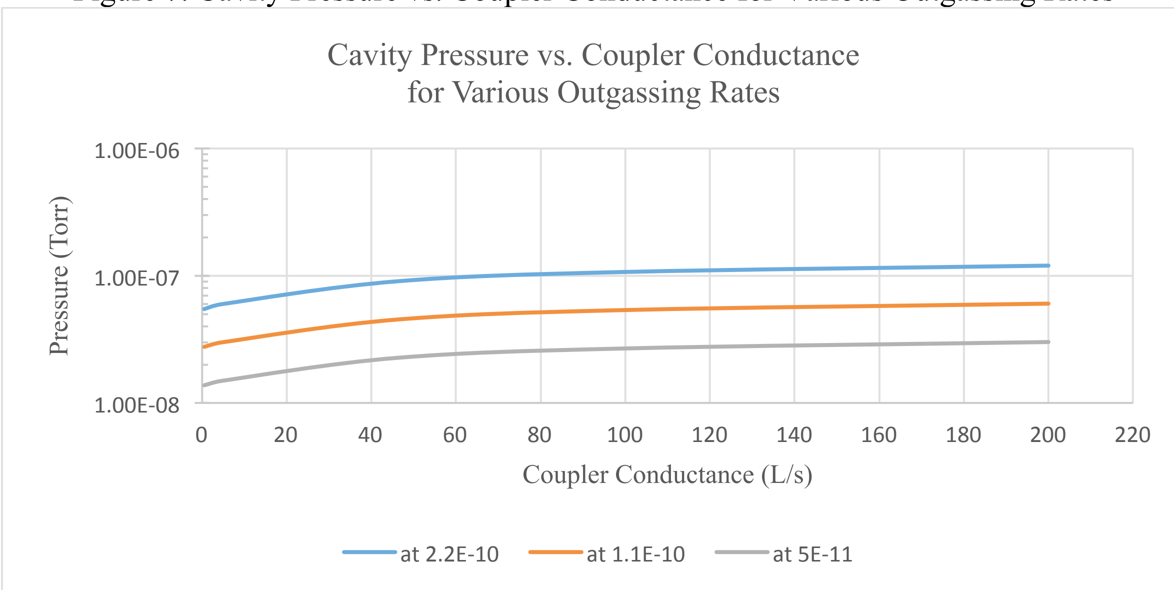


Figure 6. Pressure as a Function of Coupler Conductance



It can be seen that for coupler conductances above 60 L/s there is little change in the vessel or cavity pressures. Even reducing the coupler conductance to zero only gives a factor of two improvement in the cavity pressure (1E-7 to 5E-8 Torr). Larger effects are seen when the gas load is used as an input variable, as can be seen in figure 7. The best estimate for the bulk outgassing rate is 2.2E-10 Torr-L/s-cm^2 after about eleven days of pumping. This will improve with time under vacuum but will probably come back to the base number after subsequent venting.

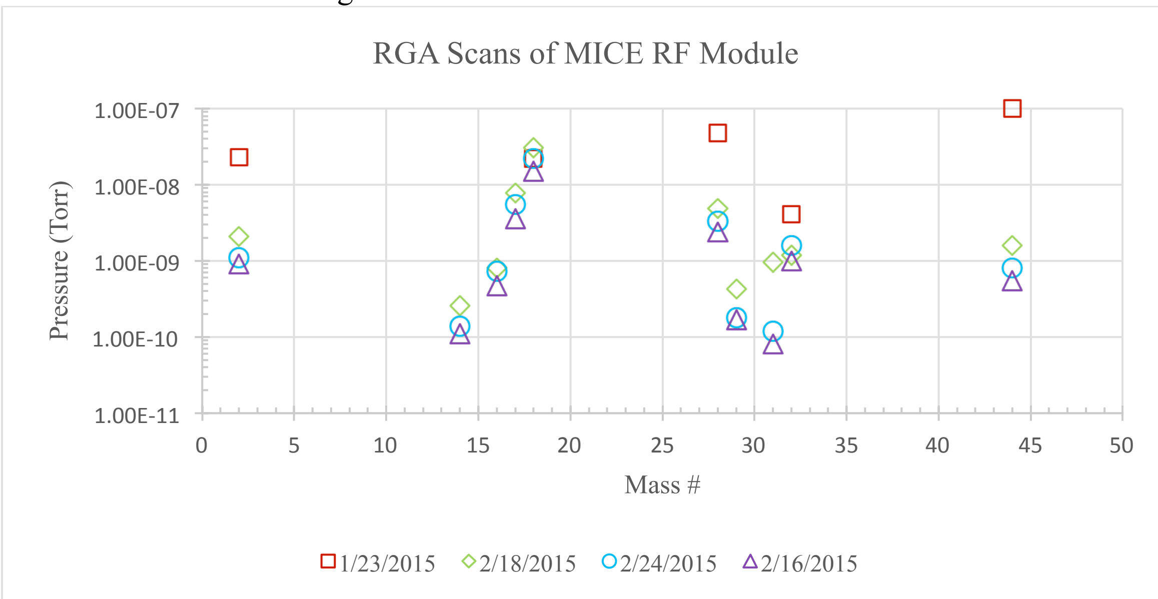
Figure 7. Cavity Pressure vs. Coupler Conductance for Various Outgassing Rates



In addition to looking at the quantity of the vacuum system (gas loads, outgassing rates, and pressures) the quality (gas composition) was also looked at. Figure 8, below, is a plot of various residual gas analysis (RGA) scans taken at various times. The 1/23/2015 scan was taken at the top port of the vessel which samples the cavity through small tubing as shown in figure 3. At the time there was a known nitrogen leak to vacuum from one of the actuator feedthroughs. The scan shows H_2, H_2O, N_2/CO, O_2, and CO_2. The CO_2 was determined to come from the hot filaments on the ion gauges and the RGA, and is therefore of little concern. The high 28 peak is mostly N_2 in this scan and comes from the known leak. It is not clear where the O_2 peak is coming from. It could be from air in the leaking N_2 line or virtual in nature. Discounting the problematic levels of CO_2 and N_2 we are left with H_2, H_2O, N_2/CO, and CO_2. H_2 and H_2O are at equivalent levels (low E-8 Torr) and N_2/CO and CO_2 are at levels a decade or more lower. This is consistent with a clean unbaked stainless steel or copper system.

The three scans in February 2015 were taken during the second pumpdown of the system prior to the test run. The RGA was located on the side of the vessel and therefore directly sampled the gas in the vessel. There was a known air to vacuum leak in the left coupler arm during this pumpdown. The leak was repaired with epoxy but then became a source for a virtual leak. This is evidenced by the 29 and 31 peaks (alcohols). Alcohol was applied to the leak prior to applying the epoxy and remained in the crack as a virtual leak. It is clearly seen decreasing with time. The O_2 that shows up in these scans is also assumed to be virtual in nature. In the vessel scans H_2O is the dominant peak at a couple E-8 Torr followed by N_2/CO at a few E-9 Torr. The remaining gasses are H_2, O_2, and CO_2 1E-9 Torr or less. This would be consistent with a water loaded stainless steel vessel.

Figure 8. RGA Scans of MICE RF Module



Beryllium Window Concerns:

The 201 MHz Muon Cavity Prototype has two 18 inch diameter dished beryllium windows. Beryllium is a hazardous material, so precautions must be taken to insure that if a rupture does occur personnel are not exposed to the debris. The window is 0.015 inches thick and very susceptible to fracturing due to differential pressures between the cavity and the vessel and mechanical shock. For this reason care must be taken when venting the vessel and cavity to atmosphere or working around the window.

When the vessel is open the window is exposed and is subject to normal operational risks associated with working around beryllium. Therefore no exceptional measures need to be taken other than those already in existence at Fermilab (Beryllium Handling Training Course, #FN000196).

While the vessel and cavity are under vacuum there is a risk that a catastrophic event could occur that would cause the vessel or cavity to let up suddenly. If that were to happen there could be a scenario that would cause a large enough pressure differential on opposite sides of a window to cause it to rupture. In the current configuration the cavity and vessel communicate with each other at the bottom pumping port and in the coupler arms. The conductance between the cavity and vessel is estimated to be 46 L/s. Therefore a catastrophic event that does not cause a direct impact (solid material or gas) on a window should not cause a window to rupture.

The other scenario that could cause a pressure differential is during controlled venting to atmospheric pressure when the vessel and cavity are under vacuum. This is done under procedural (Appendix 2) conditions through the bottom pumping port. A 1 to 2 psi pressure relief valve is used on the N_2 gas bottle to prevent over pressuring the system and a bypass line is valved in at the bottom of the vessel so that the vessel and cavity see the same pressure at the entrance to the two vacuum spaces.

If a window were to rupture while under vacuum conditions all debris would remain inside the vessel and cavity because all air flow would be into the vessel. The only possible exposure to personnel would be when the vessel is opened. At that time the hazard can be dealt with under controlled conditions using standard beryllium clean-up procedures. This would be a great loss in time and money to the project, but the exposure to personnel would be mitigated.

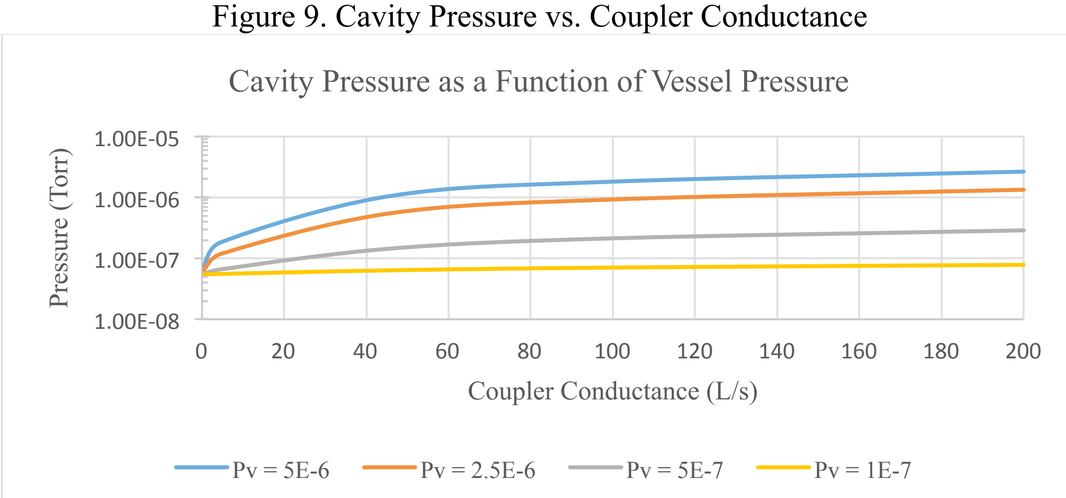
The question becomes at what deferential pressure does the integrity of the beryllium become an issue? The window is reinforced at 16.535 inches on the diameter, so the relevant stress location is at the 16.535 inch diameter. For a flat plate the maximum stress would be sigma = $6M/t^2$, where M is equal to the radial moment at the diameter and t is equal to the plate thickness. The moment is equal to q $a^2/8$, where a is equal to the radius and q is equal to the pressure differential. The ultimate strength of beryllium is about 65,000 psi, which would give a maximum pressure between the cavity and vessel of 0.2853 psi before failure. This all assumes a flat disk though, and the actual window is dished so the 0.2853 psi (14.75 Torr) is a lower bounds for failure.

A finite element analysis (FEA) was done on the dished assembly [4] that shows the beryllium yielding at a deferential pressure of 0.76 psi on the concave side and the convex side. If we allow for a safety factor of two on ultimate strength (65,000 psi for beryllium) the FEA model shows an allowable pressure deferential of 0.6 psi.

End Use at Rutherford Appleton Laboratory:

Ultimately the MICE RF module will be installed in the Muon Ionization Cooling Experiment (MICE) at Rutherford Appleton Laboratory. The vacuum performance when installed will largely depend on what the beamline vacuum conditions are there. The beamline is common with the vessel vacuum in our test, so the performance of the cavity is dependent on the pressure in the beamline. Figure 9 is a plot of the cavity pressure verses coupler conductance for various beamline pressures.

Figure 9. Cavity Pressure vs. Coupler Conductance



It can be seen that if beamline pressures are maintained in the 2E-6 to 5E-7 Torr range Cavity pressures should be maintained in the low E-7 to high E-8 Torr range if coupler conductance is limited to around 20 L/s.

Assuming that the beamline gas load is similar to that of the MICE RF module vessel being tested at Fermilab the gas load would be about 5.27E-5 Torr-L/s-m. This would require pumping speeds of 105 L/s-m to maintain a pressure of 5E-7 Torr in the beamline. That would be equivalent to one 145 L/s turbo connected directly to the outer shell via a 4" gate valve every meter. This would require the turbo to be magnetically shielded. As the diameter of the connection port is increased the pump could be moved farther away from the shell. As an example, going from a 4 inch port to a 6 inch port would allow the turbo to be moved thirty inches away from the shell. An eight inch port would allow for the turbo to be eighty inches away.

The advantage of this approach is in protecting the beryllium windows. With the connectivity of the coupler/beamline conductance there would be little danger of developing a harmful pressure deferential between the beamline and the cavity. Further modeling of the gas flow between the two volumes would be needed to specify the actual size of the conductance needed.

Vacuum Procedures:

See Appendix 1 through 5.

[1] Assembly and Testing of the First 201-MHz MICE Cavity at Fermilab, Y. Torun et al., Proceedings of the 2013 Particle Accelerator Conference.
[2] 201 MHz Muon Cavity Prototype Beryllium Window, drawing 25O640, LBNL.
[3] A 201 MHz Cavity Design with Non-Stressed Pre-Curved Be Windows for Muon Cooling Channels, D. Li et al., Proceedings of the 2003 Particle Accelerator Conference.
[4] Beryllium Window Pressure Analysis, Matthew Yerkes, Fermilab